# Optimized Power Flow in a Solar EV Charging Microgrid Using Flywheel Storage and Genetic Algorithm Control

[1]Salman Ahmed Khan, [2]Amit Kumar Asthana
[1]M. Tech Scholar, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology, Bhopal
[2] Professor & Head, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology, Bhopal
[1]salmanahmed1010kha@gmail.com , [2]asthana603@gmail.com

**Abstract:** Electric vehicles (EVs) being more in demand called forth the charging infrastructure with supply of renewable energy to be efficient, resilient, and sustainable. When the systems are charging, the grid faces heavy loads, especially when operating at peak loads. Hence, hybrid renewable systems comprising solar and wind energy tend to be a viable alternative, reinforced by intelligent control and energy storage systems. The concentration will be on the design and simulation of a solar and wind hybrid energy charging station for EV, with such other systems as dual storage-type battery and flywheel energy types. The DC bus voltage must stay steady, and the best use of energy must be made to guarantee uninterrupted charging under changes in the situation of weather and loads. The concept of a control strategy subject to deep reinforcement learning, assisted by model predictive control, for optimizing converter performance via a genetic algorithm, is introduced. Simulation using MATLAB/Simulink was developed with the intent to study system behaviour and effectiveness. It is the controller that dynamically controls the at-scale energy from renewables and storage, based on generation and EV load changes. The simulation further displays adaptability to varying irradiance and wind speeds while keeping a stable 600V DC link. Some advanced control strategies aid in voltage regulation and reduce power losses thereby improving energy efficiency. This proves the model implementation to be a worthy consideration for larger scale applications in a smart EV charging infrastructure.

**Keywords:** Electric Vehicle Charging, Deep Reinforcement Learning, Model Predictive Control, Renewable Energy Integration, Genetic Algorithm Optimization.

## I. Introduction

The solar-powered system development with EV charging stations is a major step in sustainable transport, addressing topics like carbon emission, energy dependence, and environment degradation [1]. With countries quickly developing in infrastructure and technology, emissions from industrial activity and vehicular traffic continue to increase, with the transport sector contributing 25% to Europe's $CO_2$ levels and 32% to those of the USA [2]. Electric vehicles could only be good for the environment if the energy to charge them came from renewable sources; a solar-powered charging station offers such alternatives by cutting down on carbon emissions and grid loads [3]. Microgrids with solar panels, wind turbines, and battery-containing systems are for energy systems that decentralize energy production, hence augment efficiency and provide reliable power, especially where grid access is limited or unstable [4]. Due to the variable nature of renewable sources and EV demands, intelligence is needed to enable the energy flow optimization process to balance supply and demand in real-time so as to maximize efficiency, minimize losses, and keep the grid stable [5]. Figure 1 shows a solar-powered bidirectional EV charging system where solar energy is converted and managed through both DC-DC and inverter stages to charge an EV or to supply energy to the grid.

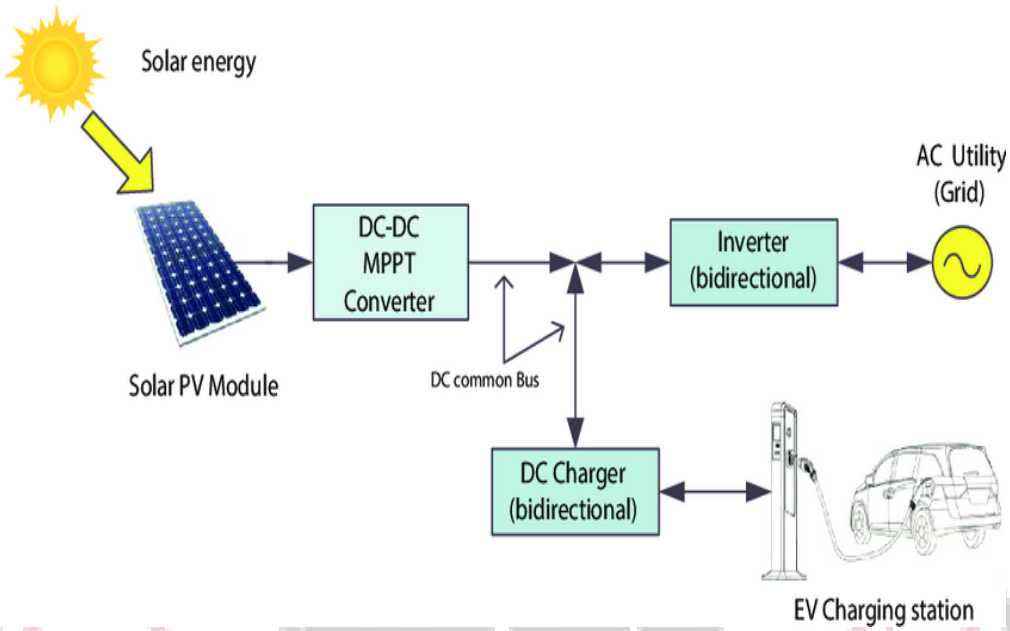


Figure 1 A basic block diagram of the solar PV grid-charging system [6]

Microgrids are state-of-the-art, decentralized, and intelligent energy systems that provide operational flexibility by functioning autonomously or in coordination with the main grid, thus contributing to regional energy autonomy and sustainability [7]. Microgrids, by integrating renewables and distributed generation with smart technologies, are coping with challenges of fluctuating energy demands, aging infrastructure, and environmental issues, while forming an infrastructure for smart grids in the evolving energy ecosystems [8]. Their clean-technology enablement and energy accessibility provision to remote or underserved areas mark their importance for decentralized, green-energy solutions [9]. Through decentralized energy management mechanisms, microgrids enable communities to generate, control, and consume electricity locally from renewable resources, thus increasing efficiency while reducing transmission losses, apart from being able to respond in nearly real-time to demand-supply dynamics [10]. Also, through enabling workings of microgrids, considerably improve the resilience of the larger grid while faced with outages and other disasters, wherein supporting critical infrastructure and sustainability efforts, integrating further renewables, lowering greenhouse gas emissions, and fostering net-zero pollution endeavors [11][12][13].

### A. Renewable Energy

The global environmental crisis is complex, with climate change standing out as an urgent challenge that has been addressed through various technical resolutions, including renewable energy, nuclear energy, and various conservation technologies, with renewable sources, especially the geological alternatives, being highlighted for their low carbon potentials [14]. Carbon dioxide removal (CDR) and solar geoengineering (SG) are also put in the limelight, with somewhat controversial ones like sulphate aerosol injection all being subject to critical review for effectiveness and unintended impacts [15]. However, at an accelerated rate stands another big challenge: ocean health, where problems like deoxygenation, acidification, diminishing phytoplankton population, and pollution grow pathogenic, calling for an extensive environmental agenda beyond mere climate mitigation [16][17][18][19]. Biodiversity loss, often viewed as a more serious threat than climate change, comprises a decline in the functional role of species and a radical change in biomass compositions, with wild animals constituting only 1% of terrestrial vertebrate biomass, all hinting that we may presently be undergoing the sixth mass extinction [20][21][22][23][24]. Because the biosphere is strongly interlinked with carbon storage and disease regulation, the bidirectional nature of climate and biodiversity crises levels calls for integrated solutions, with one hand losing biodiversity undermining carbon sequestration and amplifying threats like zoonotic diseases, and with another hand photovoltaic energy systems also requiring stricter control methodologies such as MPPT and PWM for elevated energy utilization [25]. To save the additional energy produced by photovoltaics, a central controller is required to redirect the generated power to the battery, as illustrated in Figure 2. Many scholars have investigated the sequence of controllers that are used in photovoltaics. They highlighted that it is essential to improve the productivity of solar energy generation through a maximum power point tracker (MPPT) and pulse width modulated (PWM) technologies [26].

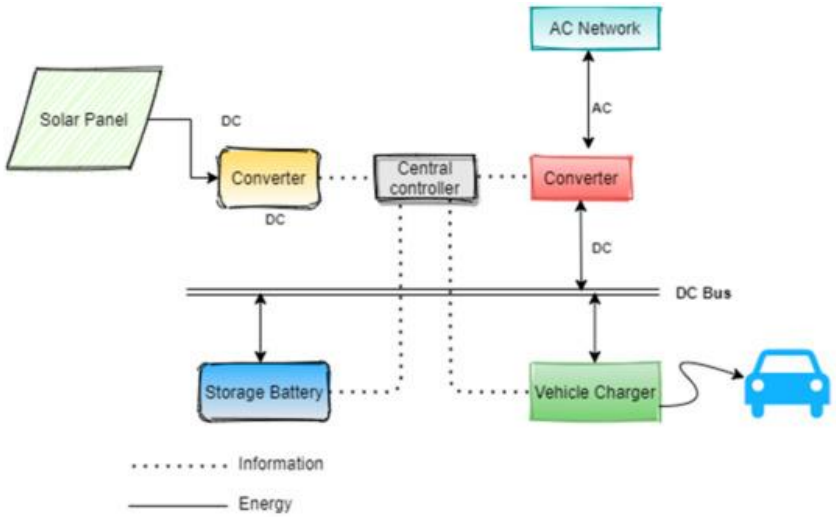


Figure 2 EV Charging Infrastructure with a Solar PV Charger [26].

### B. Electrical Vehicles

The world has developed a great thirst for electricity with the rise in electric vehicle adoption. This needs a charging infrastructure that is efficient and powered by renewables. EVs are energy efficient (80–95%) and do not emit any $CO_2$ while being operated, thus helping to reduce pollution and dependence on fossil fuel [27]. Solar or wind energy is considered cleaner and cheaper for RCI, meanwhile also lessening the stress on the grid [28]. Apart from great advantages of high efficiency and low operating costs, RCI faces problems because of the variability in renewable supply and charging demand of EVs [29]. Proper planning, sizing, and energy management are important to expand RCI and make transport sustainable [30].

## II. Literature Review

Thomas Tongxin Li et al. (2025) [55] emphasized solar electric vehicles' (solar EVs) prospects in sustainable mobility and $CO_2$ emission reduction, promoted by advances in PV technology, battery systems, and vehicle design-all while pointing out challenges related to infrastructure and grid flexibility. In the same spirit, Isha Chandra et al. (2025) [56] focused on solar-based EV charging stations, introducing the Opposition-based Competitive Swarm Optimization (OCSO) method-the OCSO method-in achieving major reductions in power loss and transformer aging by smart G2V and V2G strategies. Mohd Bilal et al. (2025) [57] studied a renewable microgrid tied to a grid for Saharanpur City, promoting renewable energy generation of up to 80% with an economic viability of hybrid optimization done over 1,164 configurations. Sandeep S D. et al. (2024) [58] presented a hybrid EV charging system comprising PV and the grid controlled by advanced converters and control methods to enable dynamic bidirectional energy flow, which was validated through MATLAB simulation. Nikita Mudaliar et al. (2024) [59] suggested a DC microgrid-based EV charging system that integrates solar, wind, and battery storage and stressed MPPT and advanced control for smooth, environment-friendly operation. D. Kavitha et al. (2024) [60] discussed the cooperation between EVs for solar charging towards a clean, low-emission transport system, while Himabindu N. et al. (2023) [61] proposed a biogas-solar hybrid charging model for Karnataka, exhibiting tremendous advantage from the environment and grid-independent perspective. Seyed Ali Kashani et al. (2022) [62] reviewed solar-integrated wireless power transfer (WPT) EV charging, concluding that intelligent control is the key to efficient and contactless energy delivery. Singgih Dwi Prasetyo et al. (2022) [63] established the possibility of solar-powered EV charging in Indonesia, further supporting the economic viability of surplus energy for city-wise application. Finally, Mohammad Ekramul Kabir et al. (2020) [64] opened the area on fast and cheap EV charging through PV and energy storage, providing smart pricing schemes through game-theoretic models, thus proving scalable and efficient charging infrastructure solutions.

Table 2 Comparative Analysis of Key Literature on Solar PV-Based EV Charging Microgrids

| Author | Focus Area | Key Contributions | Challenges | Methodology Used | Technologies Applied |
|---|---|---|---|---|---|
| Thomas Tongxin Li et al. (2025) | Solar EV integration | On-vehicle PV systems, grid decarbonization | Infrastructure support, interdisciplinary research | Qualitative review | PV systems, EVs, battery tech |

| | | | | | |
|---|---|---|---|---|---|
| Isha Chandra et al. (2025) | OCSO optimization for EVCS | Smart G2V/V2G strategies reduce grid stress | Renewable variability, cost optimization | Simulation and optimization | OCSO algorithm, V2G, G2V |
| Mohd Bilal et al. (2025) | Grid-tied hybrid microgrid | 80% RE share, strong economic gains | System design complexity | Hybrid optimization modeling | HOMER software, solar/wind resources |
| Sandeep S D. et al. (2024) | G2V/V2G smart control with neural networks | Bidirectional energy flow, PV priority | System complexity, real-time control | MATLAB/Simulink simulation | FFNN, MPPT, 3-phase VSC |
| Nikita Mudaliar et al. (2024) | DC microgrid with MPPT, WT, PV | Uninterrupted RE-based supply | Coordination of multiple RE sources | DC microgrid simulation | MPPT, PV, WT, lithium-ion battery |
| D. Kavitha et al. (2024) | EV benefits and solar synergy | Zero emissions, operational benefits | Scaling infrastructure | Conceptual analysis | Solar-powered EVCS |
| Himabindu N. et al. (2023) | Biogas-solar hybrid EVCS | Reduced grid reliance, GHG mitigation | Location-specific resource availability | HOMER-based simulation | Biogas, solar PV, grid-tied microgrid |
| Seyed Ali Kashani et al. (2022) | Wireless power transfer with solar | AI integration in WPT, efficient energy transfer | Tech maturity, WPT component limitations | Literature review | WPT systems, AI integration |
| Singgih Dwi Prasetyo et al. (2022) | Grid-connected PV for EVCS | Surplus energy generation, revenue opportunity | Initial cost, system sizing | Techno-economic assessment | HOMER tool, PV sizing |
| Mohammad Ekramul Kabir et al. (2020) | PV + ESS with game theory | Efficient, fair, and fast charging | Computation time, real-time load forecasting | Optimization + game theory | ILP model, Game 1 & 2, ESS |

### A. Research gap

Despite the growing amount of research being conducted about solar-powered charging of EVs, certain lacunae still exist go toward real-world scaling issues, integration strategies, and the long-term performance issues of these systems in diverse environmental and grid conditions. Most literature investigates area control issues, control strategies, and optimization models and largely misses out on the scaling issues in the absence of clear field validation, standardization, and interoperability framework in varying geo-socioeconomic environments. Therefore, the interaction among solar generation variability, EV load unpredictability, and grid responsiveness remains largely unaddressed and needs to be explored with the help of interdisciplinary assertion and large-scale pilot studies. Furthermore, limited research is being conducted on the policy framework, end users' behavior, and

economic models that will enable the active and wide deployment of renewable energy-powered EV infrastructure, both for urban and rural settings.

## III. Objectives

- To design a hybrid solar-wind energy-based charging station integrated with a dual storage system comprising battery energy storage and PMSM-based energy storage for DC bus voltage stability.
- To develop a hybrid control algorithm for driving DC/AC converters so as to work on PMSM performance improvement and provide smooth grid integration.
- To energize the management of renewable sources and storage systems so that the charger's operation could be steady, effective, and reliable.
- To analyse through calculations the overall charging infrastructure of this study, and the adaptation of this system under different solar and wind input conditions.

## IV. Methodology

The ramped-up charging demands from electric and plug-in hybrids have exerted unprecedented forces on electrical grids. Hybrid systems take advantage of an internal combustion backup, whereas the EVs have batteries alone; so, range limitations and battery costs create the major concerns. Charging stations of high speed and power will reduce charging times but require enormous instantaneous power demands, thereby putting great stress on the power grid. Energy storage, especially mechanical options like flywheels, can in a good way temper peak power demands and assist with high power-for-a-short-time needs in EV infrastructure.

AI-based power management schemes for the charging stations are now being proposed to solve these problems. Metaheuristic optimization approaches are capable of dealing with very hard problems in power electronics control, including speedy parameter tuning and detecting aging. Grid-end AC/DC control is optimized using PQ methods in the dq0 reference frame, with continuous online monitoring and identification of system variables. The controllers are fed with grid parameters, load parameters, inverter parameters, etc., to generate compensation commands for active and reactive power control, and harmonic compensation and PWM signals for the inverter switching of the charger. It is also necessary to control the converters for battery discharge and PMSM speed so that the flow of energy through the driveline can be done safely and optimally. The figure 3 shows a hybrid renewable energy-based EV charging system wherein solar and wind generation sources, along with a battery and PMSM storage, are joined through a common DC line with the use of several converters to fulfill efficient energy management and distribution.

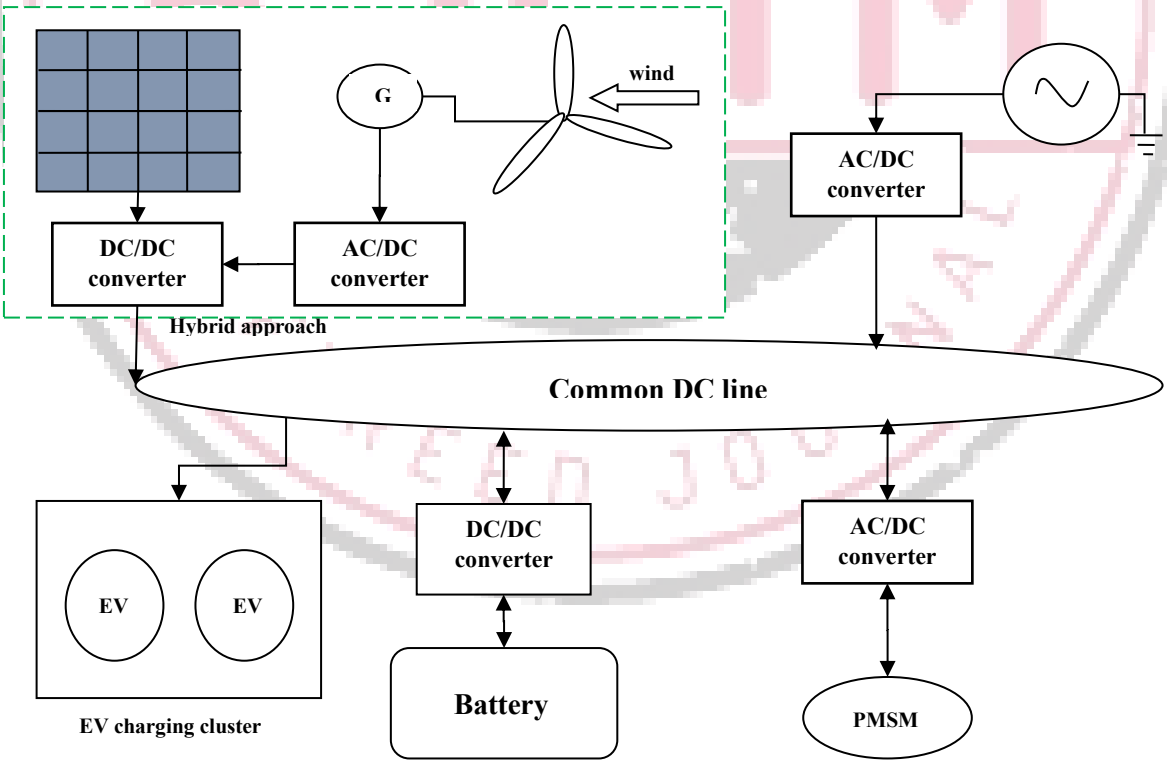


Figure 3 Hybrid approach at the charging station

### A. MATLAB modelling of a flywheel energy storage device

Motors are simulated and studied using their equivalent circuits. The motor's equivalent circuit can be obtained from the d-q modelling of the machine using the voltage at the stator equations. The electromagnetic torque

indicated in the d-q rotating frame is provided by since the wheel motors is a synchronous permanent magnetic machine (PMSM):

$T_e = \frac{3p}{2}[\Psi_{PM} i_q + i_q i_d (L_d - L_q)]$ (1)

Based on rotational dynamics, a flywheel energy storage system can be simulated in MATLAB by calculating its kinetic energy of storage, which depends on moment of inertia and angular velocity.

KE = (1/2) * I * ω^2 (2)

where I is the flywheel's moment of inertia, KE is its kinetic energy, and ω is its angular velocity.

The amount of power supplied to the flywheel is the rate at which kinetic energy changes in relation to time, and it may be written as:

$P_{in} = d\,(KE)/dt = I * \omega * d\omega/dt$ (3)

The power output from the flywheel is given by:

$P_{out} = -I * \omega * d\omega/dt$ (4)

where the flywheel's power extraction is shown by the negative sign.

The difference between power input and power output is the flywheel's net power input:

$P_{net} = P_{in} + P_{out} = I * \omega * d\omega/dt - I * \omega * d\omega/dt = 0$ (5)

Modeled herein is a flywheel energy storage system (FESS) that uses a PMSM and a back-to-back arrangement for the power operators represented by six IGBT switches. The complete system, i.e., PMSM with power converters, is controlled by an outer speed loop and an inner current loop with constant voltage regulation, the inner loop optimization being carried out by evolutionary algorithm. The main components of the FESS are the flywheel machine and the three-leg inverters, with the flywheel being modeled as a permanent magnet synchronous machine. The energy storage of the flywheel remains constant over time and is calculated by Equation 6.

$E = \frac{1}{2} J \omega^2$ (6)

where J is the wheel inertia and ω is the angular speed

The $d_q$ model of PMSM can be represented as follows:

$v_q = R_s i_q + \frac{d}{dt}\lambda_q - \omega_e \lambda_d$ (7)

$v_d = R_s i_d + \frac{d}{dt}\lambda_d - \omega_e \lambda_q$ (8)

Flywheel units consist of parallel flywheel units connected on a single DC bus, with each unit having its own flywheel machine and inverter. A capacitor exists on the DC bus between the PV converter and flywheel inverter, whereas the grid inverter is responsible for controlling the power flow to and from the DC bus and the network. The control system operates in response to changes in total power flow from sources such as PV, wind, battery, and flywheel versus load demand. The AI-based control system keeps a reference voltage by regulating flywheel power flow and reducing voltage deviations while adjusting the flywheel reference speed according to DC voltage changes.

**B. DC/AC converter control system Designing architecture control**

A typical motor drive system has a motor and a control system fed by a power converter. This power converter converts DC voltage into a three phase AC voltage to drive the motor which in turn converts electrical energy to mechanical energy to work the load. The voltage source inverter (VSI) is very commonly used in an adjustable speed drive to supply AC output of variable frequency and magnitude. They ordinarily use a particular switching waveform generation method while complex controls are required in AC drives to regulate both the amplitude and phase of the stator current. The current regulating action in the motion controller should ideally have an infinite bandwidth and zero steady-state error so as not to degrade performance.

The control system of the converter maintains the voltage and frequency within safety levels by using mathematical models that track the real behaviour of the converter. This involves a feedback control loop: devices that monitor the output voltage and frequency send signals to adjust the pulse width modulation (PWM) that controls the switching devices. The three-phase inverter design uses three pairs of switching devices connected between the DC source and one of the AC output phases. The PWM signals determine the duration for which these switches are ON or OFF, such that switching in a predefined sequence produces a three-phase AC waveform. A control circuit manages the PWM to keep its output within the voltage and frequency specification at all times (see Figure 4).

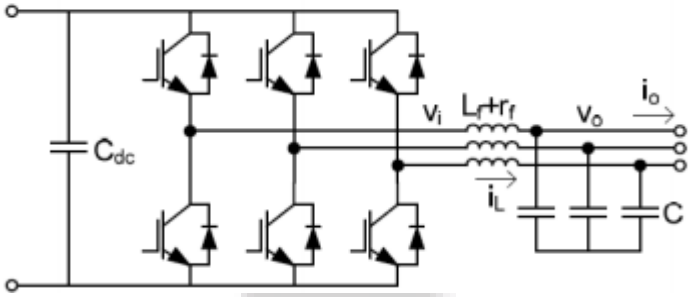


Figure 4 Block diagram of three phase inverter.

Table 3 Inverter Parameters

| Power electronic device | IGBT/Diodes |
|---|---|
| Snubber resistance | 5000 ohms |
| Forward voltages | 0 |
| Ron | $1x10^{-3}$ ohms |

To convert the three-phase voltages $V_{abc}$ into the factors $V_{dq0}$ in the frame of reference in their rotor, the indicated equations are developed.

**C. Power flow genetic algorithm (OPGA) for Converter Control**

Parametric methods are traditional system identification methods, and the main drawback of these methods lies in the possibility of setting parameters incorrectly and the instability faced by the system through this. However, AI-based optimization methods are increasingly being deployed, especially GAs, because they have global search capabilities and can efficiently solve nonlinear problems. These algorithms imitate selection in nature: in an iterative sequence of selection, crossover, and mutation, the best solutions are sought. More specifically, optimization will be carried out in selecting initial weights and tuning PID gains to minimize overshoot and settling time, so as to improve dynamic and steady-state responses. The behavior of the system is modeled through a control loop that accommodates voltage and frequency changes by means of pulse width modulation (PWM) signals; in this case, the objective function aims at minimizing the performance errors induced by disturbances.

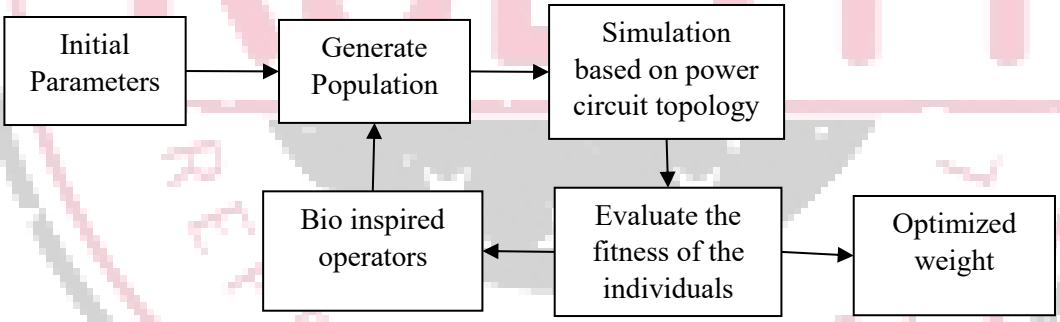


Figure 5 Operation of the optimization scheme

Figure 5 shows the GA finds the most desirable switching pattern in minimizing any lower-order harmonics in a Voltage Source Inverter. The basic process of the GA is: first, the population is initialized with random switching angles; their fitness evaluation is carried out based on the objective function, and any constraint violations are punished with a penalty coefficient. Then, from selection, crossover, and mutation, with their given probabilities based on the diversity in genetic population, a new population of solutions emerges. Elitism is implemented to preserve the elite chromosomes into the new generation. Then, the algorithm either finishes by hitting the maximum number of generations or does not show any improvement for a while. Some of the important parameters are as follows: the population being 50, the maximum number of generations 100, crossover rate 0.8, and mutation rate 0.01. Such a methodology has been embraced for real-time adaptation of control logic—particularly at charging stations running on renewables—with added flexibility for retuning as it works under different operating conditions shows in figure 6.

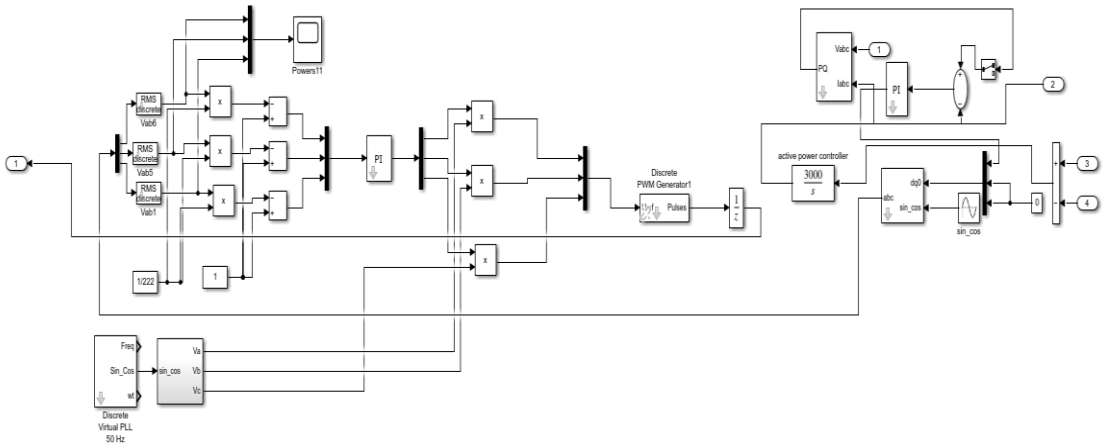


Figure 6 Control Logic Implementation in solar based CS

### D. Wind Energy system Modelling

Wind energy is one of the fastest-growing renewable energy sources due to its cost-effectiveness, efficiency, and environmental benefits. Wind turbines convert the kinetic energy of wind into mechanical energy, which is then transformed into electrical energy by a generator. The primary components include the rotor hub and blades—typically large, airplane wing-shaped structures arranged in a three-blade configuration. The pitch drive controls blade rotation speed, maintaining it within an optimal range of 1000–3600 RPM. When wind flows over the blades, the rotor turns the main shaft connected to the generator, which produces electricity by converting mechanical rotation into electrical power. Wind turbines often use Permanent Magnet Synchronous Generators (PMSG) for efficient energy conversion presented in figure 7.

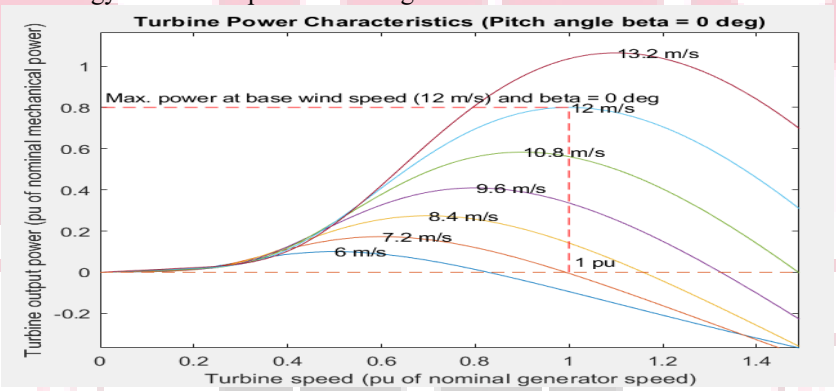


Figure 7 Wind Turbine characteristic cure used in MATLAB at different wind speeds

Table 4.2: Permanent magnet synchronous generator parameters

| | |
|---|---|
| Wind speed | variable |
| Stator Phase Resistance Rs (ohm) | 0.425 |
| Armature Inductance (H) | 0.000835 |
| Frequency | 50 hertz |
| Flux linkage | 0.433 |
| Friction factor | 0.01 |
| Pole pairs | 4 |
| Viscous Damping | 4.5 |

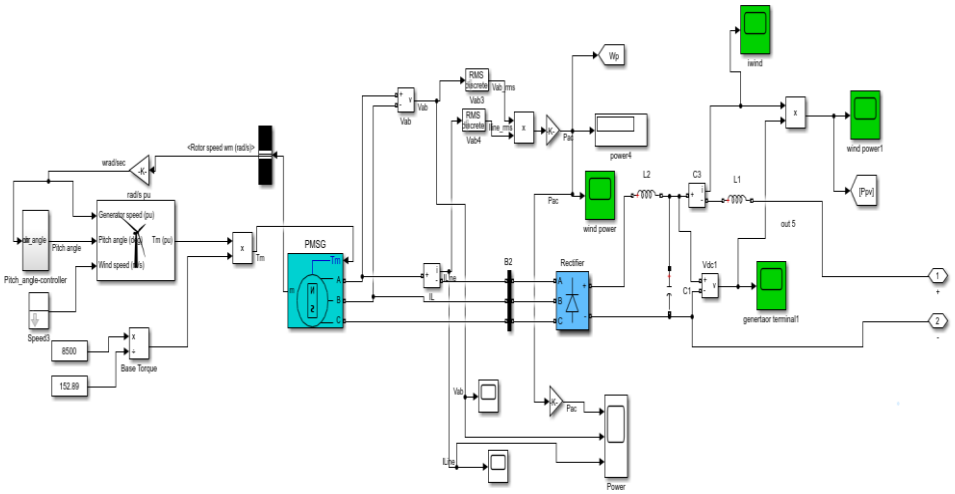


Figure 8 Modelled Wind system

The figure 8 shows a MATLAB/Simulink model of a wind energy conversion system using a Permanent Magnet Synchronous Generator (PMSG), rectifier, and filter components to convert wind power into regulated electrical output at the generator terminal. There are several equations such flying aerodynamic power, torque, and tip-speed ratio involved in the mathematical modeling of a wind energy system. The output power of the turbine depends mainly on air density, rotor area, wind speed, and power coefficient $C_p$ The blade pitch angle β being a parameter for a function of the tip-speed ratio λ. MPPT keeps the system running at maximum efficiency to extract power for any given wind speed by adjusting the turbine speed. Through MATLAB simulation, the governing system equations are studied to observe its behavior under different conditions and hence improve its design and control strategies. Extensions of these models shall be made to take into account mechanical, electrical, and grid interaction systems for wind energy systems so as to enhance efficiency and reliability further.

### E. Renewable energy resources modelling

Built-in tools such as Simulink and Simscape allow MATLAB to be regarded as an ideal platform for engineering and simulation of renewable charging stations. Systems are first defined by describing components such as solar panels, batteries, inverters, and EV chargers; then, mathematical models governing these components' behavior are drawn up; next, with resulting behaviors simulated under specified conditions, and finally, results are analyzed graphically. In the case of solar energy system modeling, components may be connected either in series or in parallel, and measurement data on energy irradiance, temperature, etc., are fed as input data to simulate system performance with the "sim" command. The crux of the equations models each part: voltage generation of the solar panel, regulation mechanism action of the charge controller, reaction of the battery voltage, and inverter efficiency. They are then united to enable the design, optimization, and analysis of solar-powered charging stations. The figure 9 shows a MATLAB/Simulink schematic of a solar PV system using the Kyocera KD300GX-LPB panel and powered by an MPPT algorithm and a DC-DC converter that controls the output power in feeding a predetermined DC load through a DC link.

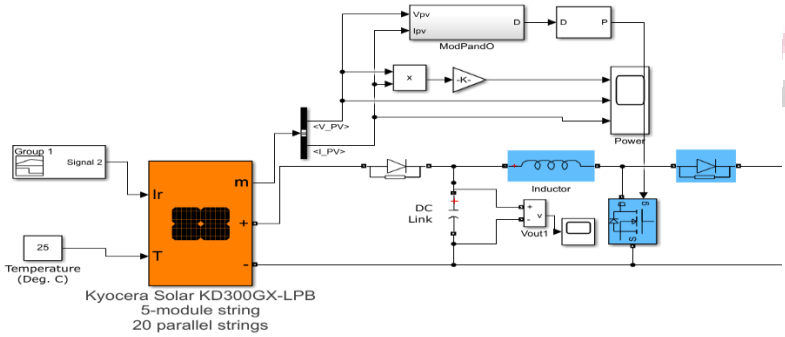


Figure 9 MATLAB Model of Developed solar based energy system for charging station

## V. Results and Discussion

A MATLAB/SIMULINK-based simulation model is developed for a 25kW solar charging station interfacing dual energy storage systems: a 5kW flywheel and a battery with an initial 60% state of charge. The station supports 5kW DC load and two 5kW AC loads through a DC/AC inverter, implemented through a standard Voltage Modulation Control (VMC) method and an optimized power flow using genetic algorithms (OPGA). They maintain a stable 600 V DC link, with GA-based multi-stage optimization maximising power quality and voltage

stability. The charging station is studied under varying solar irradiance and temperature profiles and reveals their effect on I-V and P-V characteristics, with particularity to current increase with irradiance and efficiency decrease with temperature. Making the model wind energy-compatible allows power distribution analyses, and a 20x5 solar cell array has been considered for the simulations. The two controller systems are subsequently compared for converter performances in renewable-driven charging stations shows in figure 10.

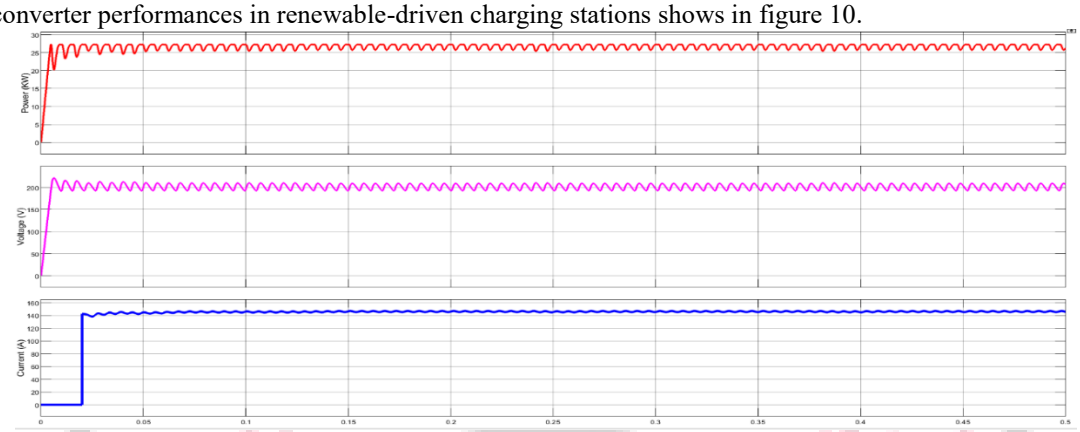


Figure 10 Output from the solar array with 1000W/m$^2$ feeding in the charging station (a) Power Output in KW (b) Voltage (c) Current Output

The irradiation levels of the solar inputs are set to be variable from 400 W/ m2 to 1000 W/m2. Increase and decrease Irradiance affects the photon-generated current; only a lower drop occurs for the open circuit voltage. The short circuit current (Isc) is directly proportional to solar insolation (Irradiation). During the simulation, the irradiation input is reduced to 600 W/m2 at 0.1 second of the simulation. Then the irradiation level is further reduced to 400 W/m2 at the simulation time of 0.3 seconds. Afterward, the analysis is extended to the figure 11.

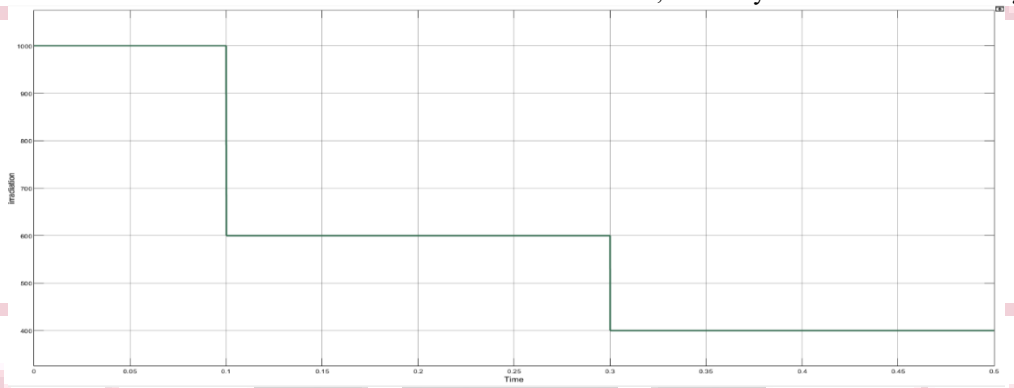


Figure 11 Variable Irradiation input to the solar system-based CS

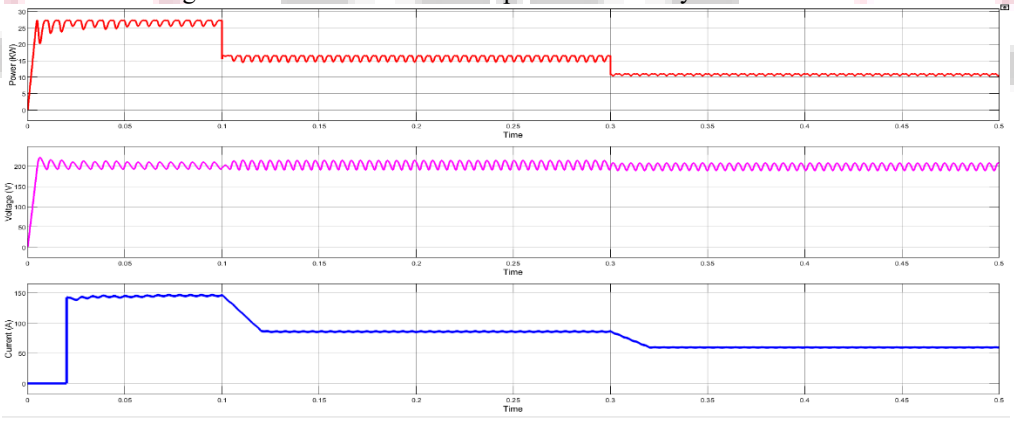


Figure 12 Output from the solar array with variable irradiations feeding in the charging station (a) Power Output in KW (b) Voltage (c) Current Output

The figure 12 indicates some changes happening in the output current and subsequently, the output solar power in the system supplying the charging station. The output power is decreased from 25KW to 15KW when the irradiation is reduced to 600W/m$^2$ and then further decreased once the flux is reduced to 400W/m$^2$ bringing the voltage levels down to 10KW.

### A. Proposed controller assessment with the Wind energy system integration to charging station architecture in system 2

In the simulation setup, the hybrid charging station brings together an 11-kW wind energy system and a 25-kW solar system to test under two scenarios: full-power operation at maximum efficiency and part operation at half input. The EV charging capacity is increased to 10 kW (for two EVs), with DC and AC loads remaining constant at 5 and 10 kW, respectively. Under cast-perfect conditions—1000 W/m² solar irradiance and 15 m/s wind—the system outputs 25 kW (solar) and 11 kW (wind) to meet 25 kW of loads while sufficiently providing energy for flywheel charging, battery storage, and EVs.

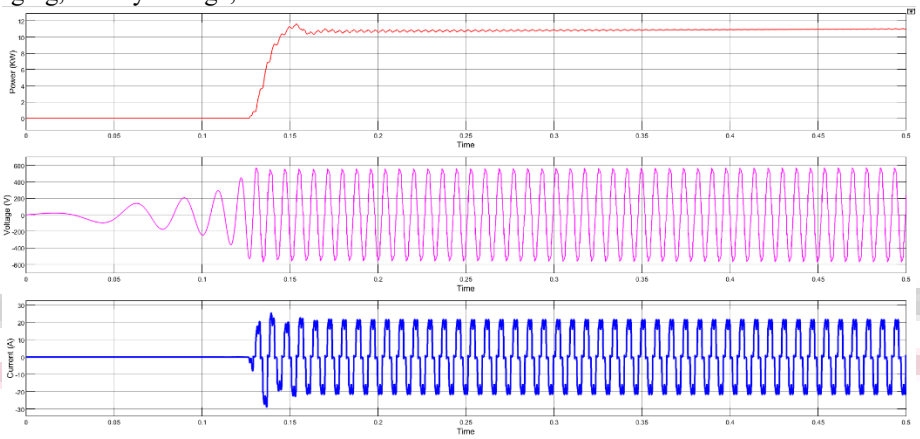


Figure 13 Output wind energy system parameters for the charging station architecture (a) Power Output in KW (b) Voltage (c) Current Output

Having the wind energy system operated under optimum input conditions, an output of 11KW is produced, as represented in the figure 13. The voltage and current waveforms are also shown with respect to the device.

### B. Analysis with Reduced Efficiency Operating Conditions

In the case of solar and wind energy, systems operating under perfect efficiency get reduced in their pressure to produce less output power here. For instance, the solar energy system receives an irradiation level of 600 watts per square metre at 0.2 seconds, which reduces the output power from the Solar to 15 KW. The same happens to the wind energy system; reduced input wind speed causes reductions in power output and available power from the wind system. Therefore, the wind system power available after 0.2 seconds equals 5 kilowatts.

Electric vehicle loads remain intact up to 10 kilowatts. Other loads eat up 15 kilowatts in total. The DC load takes 5KW, and the AC loads draw 10 kilowatts. So, the total load on the hybrid Renewable energy system is 25 kW, with solar and wind generating 20 kW. That rest of 5 kW of requiring power would be delivered by energy storage systems, where power would be drawn evenly from both BESS and FESS.

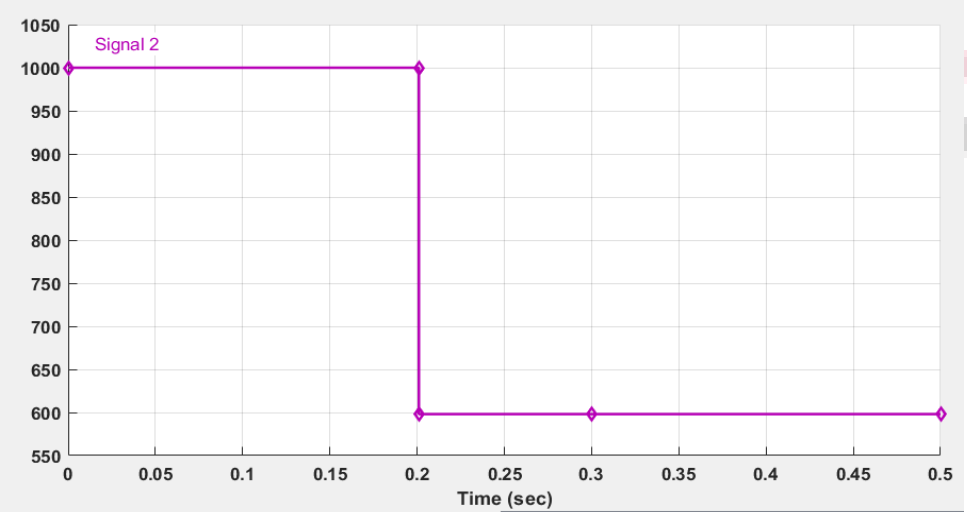


Figure 14 Variation in the irradiation level provided to the solar system

The irradiation input provided to the Solar Energy in hybrid charging station is shown in figure 14. It can be observed that at 0.2 seconds the irradiation level is reduced from 1000 W/m$^2$ to 600 W/m$^2$

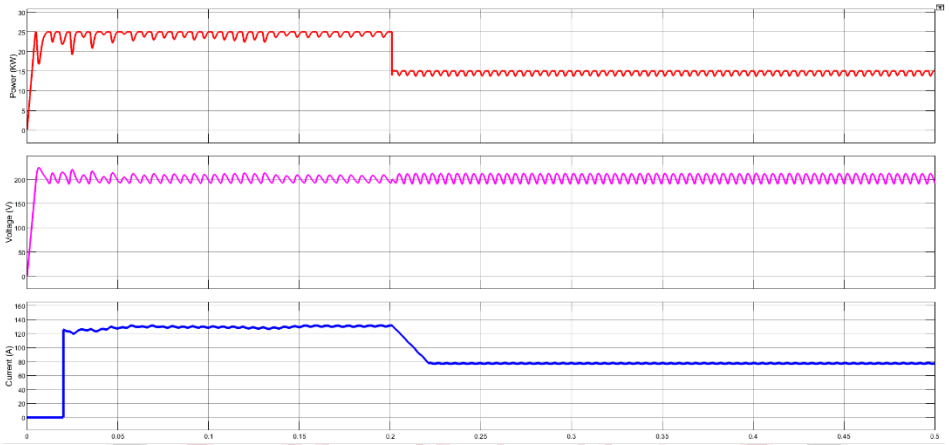


Figure 15 Power outputs from the solar system at variable inputs in hybrid CS (a) Power Output in KW (b) Voltage (c) Current Output

The figure 15 shows variations in power output from the solar system correspondent to changes in irradiation level. As against that, the power is reduced from 25 kilowatt to 15 kilowatt at 0.2 seconds when the radiation level is reduced as input into the solar energy module.

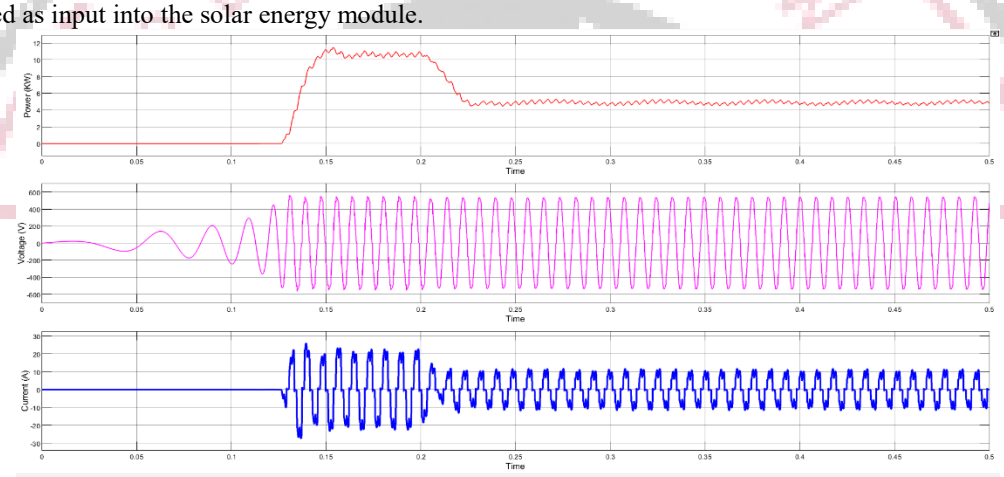


Figure 16 Power outputs from the solar system at variable inputs in hybrid CS (a) Power Output in KW (b) Voltage (c) Current Output

The figure 16 shows the changes of power in the wind system in relation to speed-level variations. The power gets reduced from 11 kilowatt to 5 kilowatt at 0.2 seconds when there happens to be a change in input parameters to the generator.

## VI. Conclusion

The hybrid charging station proposed maximally differentiates solar and wind energy with two energy storage systems into a stable, efficient, and sustainable solution for EV charging. The control strategy, assisted by deep reinforcement learning, and the converter optimization, carried out through a genetic algorithm, constitute enhanced voltage regulation, higher power quality, and greater operational flexibility. Through simulations, the system proved highly robust against environmental condition changes and variable load demands, thus validating the model towards real-world application. This study provides a major contribution to the development of the empowered renewable EV concept and supports the overarching transition towards low-carbon and smart transportation ecosystems.

## References

[1] Nawaz, M. U., Qureshi, M. S., & Umar, S. (2024). Integration of solar energy systems with electric vehicle charging infrastructure: challenges and opportunity. *Revista Espanola de Documentacion Cientifica*, *18*(02), 1-18.

[2] Barman, P., Dutta, L., Bordoloi, S., Kalita, A., Buragohain, P., Bharali, S., & Azzopardi, B. (2023). Renewable energy integration with electric vehicle technology: A review of the existing smart charging approaches. *Renewable and Sustainable Energy Reviews*, *183*, 113518.

[3] Rwamurangwa, E., Gonzalez, J. D., & Butare, A. (2022). Integration of EV in the Grid Management: The Grid Behavior in Case of Simultaneous EV Charging-Discharging with the PV Solar Energy Injection. *Electricity*, *3*(4), 563-585.

[4] Razmi, D., & Lu, T. (2022). A literature review of the control challenges of distributed energy resources based on microgrids (MGs): past, present and future. *Energies*, *15*(13), 4676.
[5] Gilani, M. A., Kazemi, A., & Ghasemi, M. (2020). Distribution system resilience enhancement by microgrid formation considering distributed energy resources. *Energy*, *191*, 116442.
[6] Husain, Mohammed & Ahmad, Waseem & Bakhsh, Farhad & Padmanaban, Sanjeevikumar & Malik, Hasmat & Khan, Rashid & Islam, Noorul & Ahmad, Seerin & Sabir, Bushra & Liu, Hwa Dong. (2024). Advances in Solar PV-Powered Electric Vehicle Charging System. 10.1002/9781394167678.ch4.
[7] Kostenko, G., & Zaporozhets, A. (2023). Enhancing of the power system resilience through the application of micro power systems (microgrid) with renewable distributed generation. *System Research in Energy*, (3 (74)), 25-38.
[8] Sahebkar Farkhani, J., Zareein, M., Najafi, A., Melicio, R., & Rodrigues, E. M. (2020). The power system and microgrid protection—A review. *Applied Sciences*, *10*(22), 8271.
[9] Wu, Y., Wu, Y., Cimen, H., Vasquez, J. C., & Guerrero, J. M. (2022). Towards collective energy Community: Potential roles of microgrid and blockchain to go beyond P2P energy trading. *Applied Energy*, *314*, 119003.
[10] Elkazaz, M., Sumner, M., & Thomas, D. (2021). A hierarchical and decentralized energy management system for peer-to-peer energy trading. *Applied Energy*, *291*, 116766.
[11] Wynn, S. L. L., Boonraksa, T., Boonraksa, P., Pinthurat, W., & Marungsri, B. (2023). Decentralized energy management system in microgrid considering uncertainty and demand response. *Electronics*, *12*(1), 237.
[12] Amin, S. M., Hossain, N., Lipu, M. S. H., Urooj, S., & Akter, A. (2023). Development of a PV/Battery Micro-Grid for a data center in Bangladesh: Resilience and Sustainability analysis. *Sustainability*, *15*(22), 15691.
[13] Lagrange, A., de Simón-Martín, M., González-Martínez, A., Bracco, S., & Rosales-Asensio, E. (2020). Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: An application to a hospital. *International Journal of Electrical Power & Energy Systems*, *119*, 105865.
[14] Deshmukh, M. K. G., Sameeroddin, M., Abdul, D., & Sattar, M. A. (2023). Renewable energy in the 21st century: A review. *Materials Today: Proceedings*, *80*, 1756-1759.
[15] Sayed, E. T., Olabi, A. G., Alami, A. H., Radwan, A., Mdallal, A., Rezk, A., & Abdelkareem, M. A. (2023). Renewable energy and energy storage systems. *Energies*, *16*(3), 1415.
[16] Olabi, A. G., & Abdelkareem, M. A. (2022). Renewable energy and climate change. *Renewable and Sustainable Energy Reviews*, *158*, 112111.
[17] Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., ... & Jaszczur, M. (2024). The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, *48*, 100545.
[18] Liu, Y., & Feng, C. (2023). Promoting renewable energy through national energy legislation. *Energy Economics*, *118*, 106504.
[19] Hassan, Q., Algburi, S., Sameen, A. Z., Al-Musawi, T. J., Al-Jiboory, A. K., Salman, H. M., ... & Jaszczur, M. (2024). A comprehensive review of international renewable energy growth. *Energy and built environment*.
[20] Li, L., Lin, J., Wu, N., Xie, S., Meng, C., Zheng, Y., ... & Zhao, Y. (2022). Review and outlook on the international renewable energy development. *Energy and Built Environment*, *3*(2), 139-157.
[21] Østergaard, P. A., Duic, N., Noorollahi, Y., & Kalogirou, S. (2022). Renewable energy for sustainable development. *Renewable energy*, *199*, 1145-1152.
[22] Dey, S., Sreenivasulu, A., Veerendra, G. T. N., Rao, K. V., & Babu, P. A. (2022). Renewable energy present status and future potentials in India: An overview. *Innovation and Green Development*, *1*(1), 100006.
[23] Guchhait, R., & Sarkar, B. (2023). Increasing growth of renewable energy: A state of art. *Energies*, *16*(6), 2665.
[24] Vakulchuk, R., Overland, I., & Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable and sustainable energy reviews*, *122*, 109547.
[25] Halkos, G. E., & Gkampoura, E. C. (2020). Reviewing usage, potentials, and limitations of renewable energy sources. *Energies*, *13*(11), 2906.
[26] Guney M S and Tepe Y 2017. Classification and assement of energy storage systems. Renewable and Sustainable Energy Reviews 75. ScienceDirect, 1187–97.
[27] Sanguesa, J. A., Torres-Sanz, V., Garrido, P., Martinez, F. J., & Marquez-Barja, J. M. (2021). A review on electric vehicles: Technologies and challenges. *Smart Cities*, *4*(1), 372-404.
[28] Sharma, S., Panwar, A. K., & Tripathi, M. M. (2020). Storage technologies for electric vehicles. *Journal of traffic and transportation engineering (english edition)*, *7*(3), 340-361.
[29] Rajper, S. Z., & Albrecht, J. (2020). Prospects of electric vehicles in the developing countries: A literature review. *Sustainability*, *12*(5), 1906.

[30] Agamloh, E., Von Jouanne, A., & Yokochi, A. (2020). An overview of electric machine trends in modern electric vehicles. *Machines*, *8*(2), 20.
[31] Li, T. T., Zhao, A. P., Wang, Y., Li, S., Fei, J., Wang, Z., & Xiang, Y. (2025). Integrating solar-powered electric vehicles into sustainable energy systems. *Nature Reviews Electrical Engineering*, 1-13.
[32] Chandra, I., Singh, N.K., Samuel, P. *et al.* Optimal scheduling of solar powered EV charging stations in a radial distribution system using opposition-based competitive swarm optimization. *Sci Rep* **15**, 4880 (2025).
[33] Bilal, M., Samiullah, M., & Hameed, S. (2025). Optimal Design and Techno-Economic Analysis of a Grid-Tied Microgrid for Electric Vehicle Charging Applications. *Transportation Research Procedia*, *84*, 426-433.
[34] Sandeep, S. D., & Mohanty, S. (2024, February). Design of Solar Powered Grid for Application in Electric Vehicle Charging Station. In 2024 Second International Conference on Emerging Trends in Information Technology and Engineering (ICETITE) (pp. 1-6). IEEE.
[35] Mudaliar, N., & Khubalkar, S. (2024, August). Integrating solar and wind power in a DC microgrid for electric vehicle charging. In *AIP Conference Proceedings* (Vol. 3139, No. 1, p. 040004). AIP Publishing LLC.
[36] Kavitha, D., Sharmila, B., Ramkumar, M. S., Sivaramkrishnan, M., & Brindha, M. (2024, November). A Retrospective of Solar-Powered Charging Stations and E-Vehicles. In 2024 8th International Conference on Electronics, Communication and Aerospace Technology (ICECA) (pp. 131-135). IEEE.
[37] Himabindu, N., Hampannavar, S., Deepa, B., Longe, O. M., Mansani, S., & Komanapalli, V. (2023). Assessment of microgrid integrated biogas–photovoltaic powered Electric Vehicle Charging Station (EVCS) for sustainable future. Energy Reports, 9, 139-143.
[38] Kashani, S. A., Soleimani, A., Khosravi, A., & Mirsalim, M. (2022). State-of-the-art research on wireless charging of electric vehicles using solar energy. *Energies*, *16*(1), 282.
[39] Prasetyo, S. D., Regannanta, F. J., Mauludin, M. S., & Arifin, Z. (2023). Economic feasibility of solar-powered electric vehicle charging stations: A case study in Ngawi, Indonesia. *Mechatron. Intell. Transp. Syst*, *2*, 201-210.
[40] Kabir, M. E., Assi, C., Tushar, M. H. K., & Yan, J. (2020). Optimal scheduling of EV charging at a solar power-based charging station. *IEEE Systems Journal*, *14*(3), 4221-4231.



inprotected.com